15. Psychological and Physiological Skill Development—A Control Engineering Model*

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The application of servomechanism models to the description of human control behavior in either manual or physiological control has generally proceeded by creating circumstances under which behavior would be time stationary in an engineering sense over the duration of the measurements. Remarkably effective stationary steady-state models were achieved and applied with considerable success to the design of complex man-machine control systems. Little attention was paid to defining the behavior whereby the human operator, acting in concert with a machine, achieves higher levels of performance as training progresses. An early attack on this question was made by Krendel and McRuer in 1960. The problem is that conventional performance measures for human manual control or physiological control, interpreted in an invariant closed-loop configuration, are either relatively insensitive to human learning behavior or are inappropriate and misleading. A restructuring of the control configurations to enable the extracting of coherence and regularities from the input structures, either physically or conceptually, is the core of the model presented. Experimental data from many sources are presented to substantiate the model, and implications for system design and training are explored.

INTRODUCTION

In 1960, Krendel and McRuer (ref. 1) presented a hypothesis for motor skills development which was compatible with the current state of knowledge in manual control and human skills training. This hypothesis held that improved human motor skill performance occurred as the operator became successively more proficient in sensing the coherence in the input signal that he was controlling. It was further maintained that the human restructured his effective control configuration to exploit the coherence that he had detected. Three control configurations were specified: a compensatory or error correcting only mode, a pursuit or target following mode, and finally a precognitive or synchronous generator

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mode. In the final mode preprogramed patterns of response are generated and timed appropriately. This hypothesis was supported by experimental evidence. In the present paper, the hypothesized configurations have been elaborated, additional empirical evidence gathered by various researchers is presented, and the dependencies of pattern generation on human precision time estimation is illustrated.

GLOSSARY

$c(t)$	operator output time function, limb position
$C(j\omega)$ or C	Fourier transform of operator output
$e(t)$	error time function
$i(t)$	forcing function time function
$I(j\omega)$ or I	Fourier transform of forcing function
K	open-loop gain
K_c	controlled element gain
$m(t)$	system output time function
$M(j\omega)$ or M	Fourier transform of system output
$n_c(t)$	operator remnant time function
$0(\ )$	order of ( )
$Y_c(j\omega)$ or Y_c	controlled element (machine and display) transfer function
$Y_p(j\omega)$ or Y_p	pilot describing function
ζ	damping ratio
σ	standard deviation
τ_e	effective time delay
Φ_{im}	cross power spectral density between i and m
Φ_{ie}	cross power spectral density between i and e
$\Phi_{ii}(\omega)$	forcing function power spectral density
ω	angular frequency, rad/sec
ω_c	system crossover frequency, i.e., frequency at which $\lvert Y_p Y_c \rvert = 1$
ω_n	undamped natural frequency
$\doteq$	approximately equal to
$\hat{x}$	estimate of x

AN ENGINEERING MODEL FOR SKILL DEVELOPMENT

INTRODUCTION.—Skill development, or any learning model, implies a change in performance characteristics as time passes and experiences aggregate. For such an adaptation to occur, the system must be able to sense the relevant aspects of its performance,

compare these with some ideal or selected criteria and, within the limits imposed by the criteria and physical realizability, modify its characteristics. It has been popular to suppose that attainment of satisfactory accuracy levels, while minimizing operator effort, are among the criteria usually involved. Indeed, it has been demonstrated that the human operator can adjust his describing function parameters to achieve minimum or low values of relative rms tracking error (ref. 2), but this performance measure may not always be the sole or even the dominant criterion to which the operator's efforts are directed.

In such an event, improvements in skill could not be measured properly by relative rms error alone and would have to be implied from describing function measurements, physiological measurements, and perhaps operator opinions obtained under carefully defined conditions, the foregoing measures taken separately or together. These measurements directly indicate changes in the operator's behavior, whereas rms tracking error may not. This point will be made clearer later in the context of our skill development models.

As the starting point in model development, let us assume that the human operator is attempting to maintain a small, visually sensed error e(t) or to minimize some function of e(t) while tracking random or random-appearing inputs in a conventional compensatory closed-loop configuration. In figure 1, this would be represented by the system elements connected with heavy lines. A considerable body of findings (refs. 2 to 4) has shown how the parameters of the operator describing function Y_{p_e}, which acts on the error signal only, are modified for different controlled elements Y_c and then adjusted during the course of learning to improve performance. In the simplest terms, the operator describing function adapted for a particular controlled element is such that the open-loop system describing function in the neighborhood of system crossover frequency ω_c approximates:

$$Y_{p_e}Y_c \doteq \frac{\omega_c}{j\omega} e^{-j\omega\tau_e} \qquad \omega = 0(\omega_c) \tag{1}$$

after adaptation of an appropriate Y_{p_e} form, the operator can improve system rms error performance by decreasing effective time delay τ_e and extending crossover frequency ω_c thereby increasing the system bandwidth and closed-loop damping. The amount of adjustment possible is limited by operator training and physical limitations, and system stability considerations. Then, once the adapted form for Y_{p_e} is optimized by parameter adjustment, the only route that allows further improvement in performance is to achieve different effective adapted forms by either selective loop closures or skill data processing.

PLAUSIBLE LOOP CLOSURES AND DATA PROCESSING.—Because both selective loop closures and data processing will be achieved by changes internal to the human operator, the nature of such changes is conjectural. One can, however, examine performance measures, open- and closed-loop describing functions, and other selected measures for control configurations that are in physical fact elaborations on the simple single-input, single-output unity feedback system. By comparing such measures with similar measures from a subject constrained to operate in what is physically the rudimentary, heavy line system of figure 1, we can imply functional correspondences between the physical elaborations and the internal developments associated with increasing skill.

In figure 1, the elaborations, beyond adaptive and optimalizing modifications in Y_{p_e}, proceed by the succession of positions of switches α and β. Switch α is in the down position, except when β is on position 2, in which case α is also on terminal 2. When only a compensatory display is present, the informational bases for the elaborations are displayed error e and operator's output c as measured by joint and other proprioceptive

receptors. As a first step, this information is sufficient for the operator to have an internal measure of his own behavior; i.e., Y_{p_e}, as a separate entity.

After some experience in controlling a given set of controlled element dynamics, there must be some measure of Y_c within the operator. For example, in terms of the crossover model, at a particular level of Y_{p_e} adaptation, an estimate, Y_c, for Y_c would be:

$$\hat{Y}_c = \frac{\omega_c e^{-j\omega\tau e}}{j\omega Y_{p_e}}, \quad \omega = 0(\omega_c) \tag{2}$$

With this measure, and the output, c(t), it is possible that the operation illustrated in the short-term memory (STM) block takes place, thus enabling a separation from the error signal of either an estimate of the input $\hat{i}(t)$, or of the input of the controlled element, $\hat{m}(t)$. Such an additional effective input can then be operated on by additional blocks Y_{p_i} or Y_{p_m}. The result is an addition to the output of the heavy-lined system given by

$$\Delta C = Y_{p_i} \hat{I} + Y_{p_m} \hat{M} \tag{3}$$

This is the pursuit level of skill development. A further possibility is that rather than operating on $\hat{i}(t)$ or $\hat{m}(t)$, the input estimate is scanned for coherence—conceptually perhaps by comparing $\hat{i}(t)$ with a "pattern file" in the long-term memory (LTM). Once a pattern is established, a free-running pattern generator could be triggered setting off an open-loop output of patterned responses via terminal 2. This is the precognitive level of skill development.

THE PURSUIT DISPLAY.—In an actual pursuit display (fig. 2), system output m and forcing function i are presented concurrently on a display. Error e may be extracted by the observer since e=i-m. Although only two of these functions are independent, three operations, symbolized by Y_{p_i}, Y_{p_e}, and Y_{p_m} are conceivable. However, no more than two are required for an analytic description of the system. For convenience, two are selected and an analysis is carried out as if they remain fixed choices. This may not be the actual mode of operation. For example, the operator may cycle his attention among the three alternatives, perhaps emphasizing two, and relying on his STM to provide estimates of the other quantities to which he is not attending. The structure labeled A and STM represents this selective attention and STM function. In figure 2, the operator's control output c contains both the results of linear operations and an additive remnant term n_c uncorrelated with i. (For simplicity, the remnant was neglected in connection with fig. 1.)

The closed-loop describing function for any utilization by the operator of the possible feedbacks and feedforward in figure 2 is M/I. It would be expected that M/I would provide a more dynamic picture of skill progression than average performance (e.g., $\overline{e^2}$) alone. Since a closed-loop description tends to supress internal details, Wasicko et al. (ref. 5) have demonstrated how an equivalent open-loop describing function Y_β can be defined after carrying out block-diagram algebra on figure 2.

$$Y_\beta = \frac{\Phi_{im}}{\Phi_{ie}} = \frac{Y_c(Y_{p_i} + Y_{p_e})}{1 - Y_c(Y_{p_m} + Y_{p_i})} \tag{4}$$

$$M/I = \frac{Y_\beta}{1 + Y_\beta} \tag{5}$$

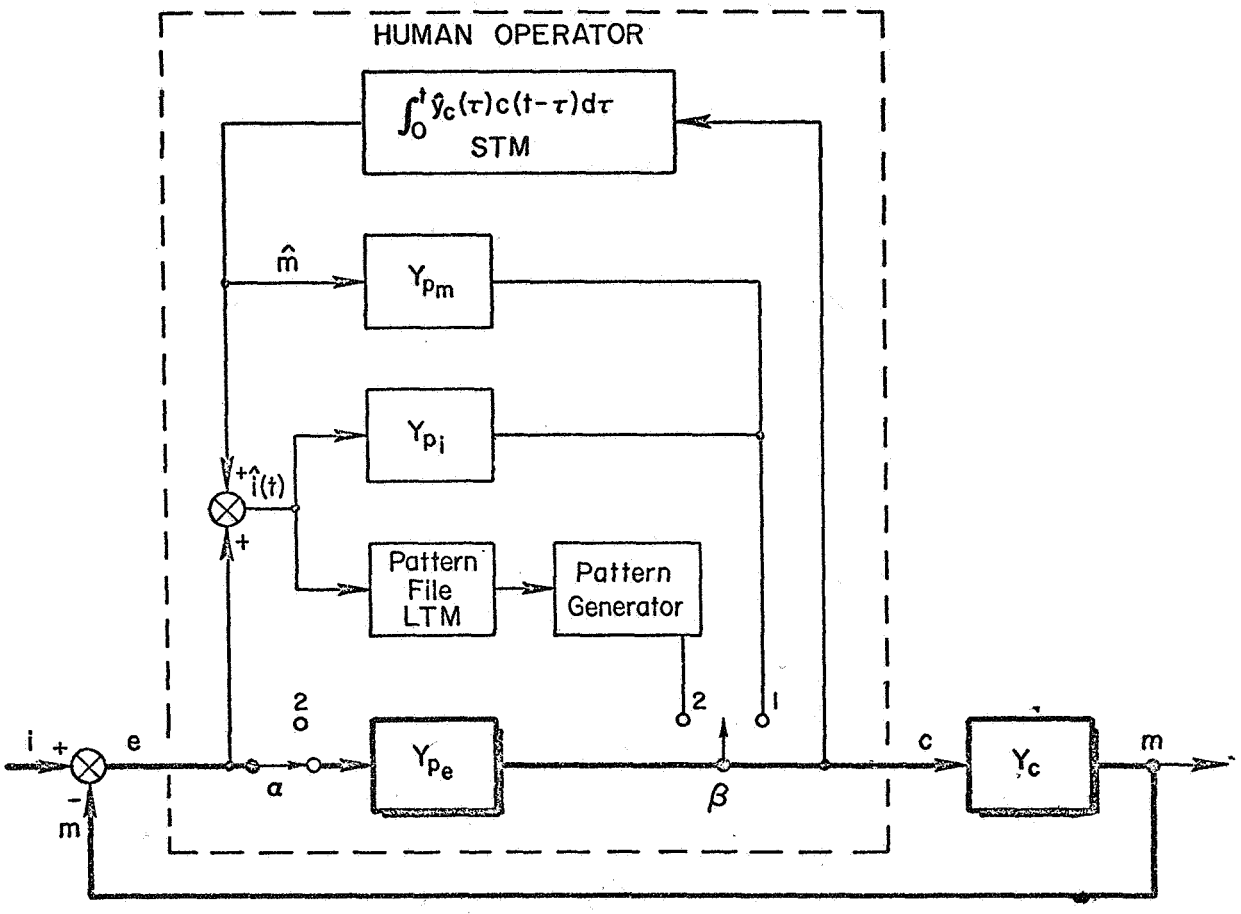

Figure 1.—Functional description of skill development—SOP.

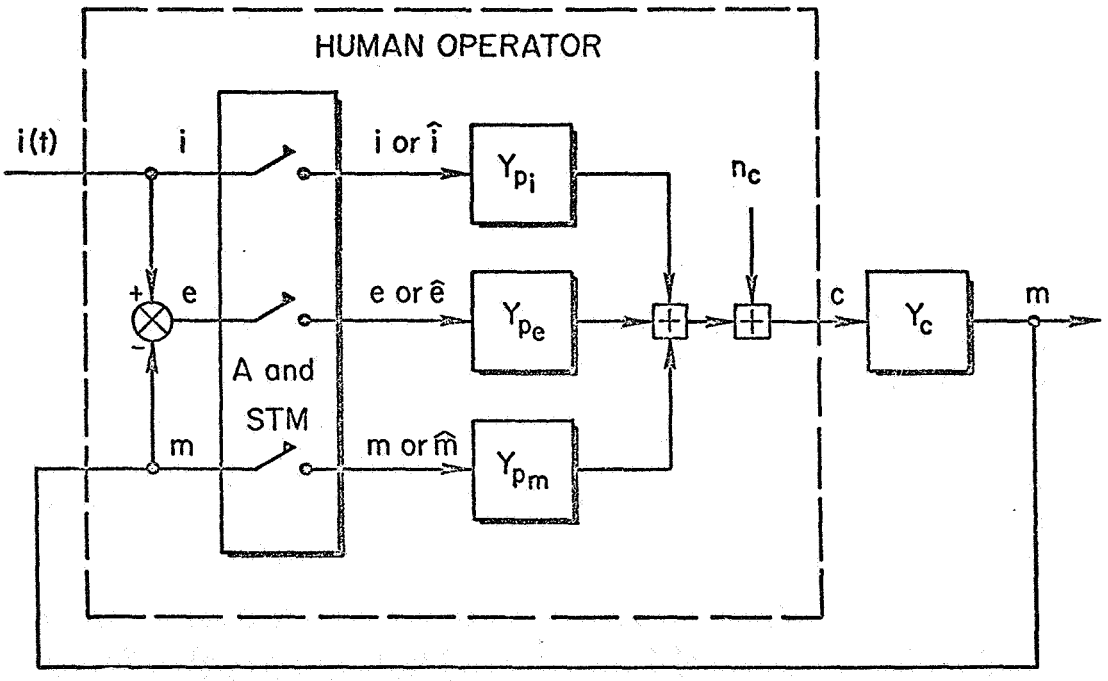

Figure 2.—The pursuit situation.

If the situation is compensatory; i.e., $Y_{p_i}=Y_{p_m}=0$, the equivalent open-loop describing function becomes simply Y_{p_e}.

The pursuit display gives the operator a greater repertory from which to adjust Y_β, so as to improve performance. The mean squared error is given by two terms: $\overline{e_i^2}$ due to operations linearly correlated with the forcing function; and $\overline{e_n^2}$ due to the remnant.[1]

$$\overline{e^2} = \overline{e^2}_i + \overline{e^2}_n \tag{6}$$

where

$$\overline{e^2} = \frac{1}{2\pi}\int_0^\infty \left| \frac{1}{1 + Y_\beta} \right|^2 \Phi_{ii}(\omega)\,d\omega, \tag{7}$$

From equations (4) and (7), the implications for the adjustment of the describing functions that comprise Y_β can be drawn. The operator must maintain a Y_{p_e} block if only to trim out drifting errors in figure 2. He may emphasize Y_{p_i} or Y_{p_m} to the practical exclusion of the other, or may cycle between them in some weighted fashion. The operator can improve some measure of average performance by increasing the effective open-loop amplitude ratio Y_β thereby increasing the effective open-loop crossover frequency. For instance, Y_β can be increased if:

$$Y_{p_i} \simeq 0 \text{ and } Y_{p_m} \simeq 1/Y_c \tag{a}$$

or

$$Y_{p_m} \simeq 0 \text{ and } Y_{p_i} \simeq 1/Y_c \tag{b}$$

Wasicko et al. (ref. 5) solved equation (4) for $Y_{p_i}Y_c$ using the assumptions that $Y_{p_m}=0$, and that Y_{p_e} was the same as that which would have been generated in an actual compensatory display with the same i(t). For controlled elements, where pursuit behavior was demonstrated; i.e., where $Y_\beta \neq Y_{p_e}$, the results are most consistent with (b) above in the region of crossover.

ULTIMATE SKILL—PRECOGNITIVE.—The pattern file, pattern generation precognitive configuration in figure 1 represents the ultimate in skill development because in it the operator can construct an estimate of the future input. With this information, he can compensate for lags inherent in the human neuromuscular system and the controlled element, thereby making the output duplicate the forcing function with no lag or even some apparent lead. Precognitive organization, because of its anticipatory nonlinear and open-loop nature (Y_{p_e} is only occasionally closed for trimming) is difficult to describe with conventional control engineering techniques. Figure 3 is a schematic for the precognitive mode of skill. In a formal manner, verbal descriptions of precognitive behavior, "deft, properly timed, appropriate loop closures, etc.," can be converted to computer-oriented flow charts and decision trees. This procedure can make the decision rules in figure 3 more explicit.

The essence of the precognitive mode is the ability to construct the future of the input signal. Examples occur in almost all of our skilled actions—in driving down a road, in docking a boat, and in signing our names, as van der Gon and Thuring (ref. 6) demonstrated. The high degree of reproducibility in a signature or holograph and the obvious lack of continuous visual feedback make it clear that writing is a programed, open-loop skill.

The precognitive mode has been studied most effectively, not in terms of preview or of everyday skills, but by means of periodic inputs that permit the description of prediction in an unambiguous manner. McRuer and Jex (ref. 7), using the available data on periodic

inputs, derived a quantitative description of the evolution of precognitive behavior in an actual compensatory display.

The process can be understood by reference to figure 1, although a remnant or noise source must be added to the operator's output c(t). McRuer and Jex (ref. 7) present their case as follows.

(1) For periodic inputs up to about 10 rad/sec (2 hertz), the operator creates a pursuit display feedforward loop in which $Y_{p_i} Y_c \doteq 1.0$, which serves to eliminate all of the time-averaged lags from his tracking. However, remnant will still excite residual errors, so a compensatory loop is also maintained, subject to similar laws of adaptation as in the random input case for very low frequency inputs. The result will be one peak in the perceived error spectrum near the input frequency and, possibly, a secondary peak near the crossover frequency.

(2) As familiarity with a particular waveform increases, Y_{p_i} takes on the form of a synchronous waveform generator that is phase locked to the zero crossings of the input. Thus, the operator's behavior becomes more and more open loop or preprogramed, and the errors at the input frequency will decrease.

(3) For inputs between about 10 and 30 rad/sec (2 to 5 hertz), the operator can no longer close the compensatory loop effectively, so crossover regression (or even complete opening of the compensatory loop) occurs. Even though the synchronous generator produces a reasonable waveform, it is no longer phase-locked to the input frequency, so shifts in phase or frequency drifting can occur.

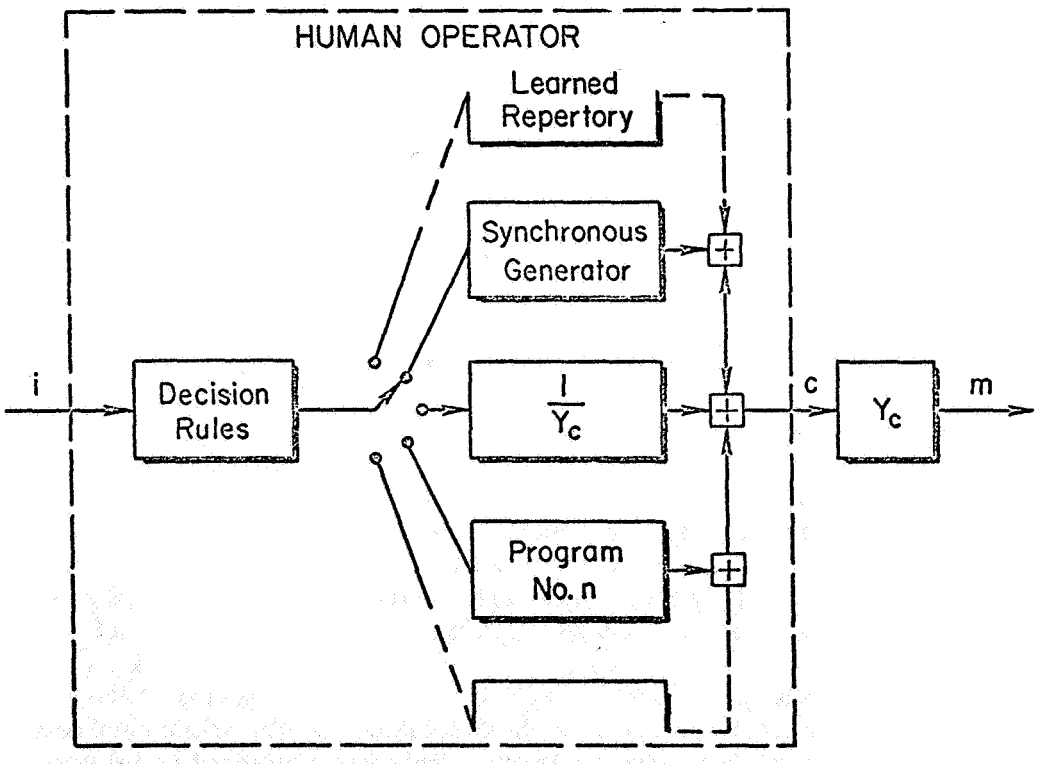

Figure 3.—Precognitive organization—ultimate skill—open loop for varying durations.

(4) The maximum periodic frequency is limited by the basic neuromuscular dynamics of the limb plus control stick, which also limits the sharpness in reproducing periodic square or triangular waveforms.

The rapidity with which most operators develop a synchronous output, at least when $Y_c=K_c$, makes it likely that phase b in the previous progression takes place within two or three cycles. This means that it is of considerable interest to discover the conditions, limits, and accuracies with which periodic inputs can be reproduced, maintained, and outputs phase-locked with these inputs.

It is well to reiterate that the schematics in figure 1 and figure 3 refer to either actual or effective display configurations. Thus, it is possible in a physical pursuit configuration for the operator to perform as if the display were, in fact, compensatory; whereas after much practice with a physically compensatory display on an input which is predictable, the operator can achieve an effective pursuit or precognitive display (refs. 8 and 9). It is the operator's level of skill, not the physical display-control configuration that determines the characteristic mode of behavior in the successive organization of perception (SOP) sequence.

PSYCHOLOGICAL AND PHYSIOLOGICAL CONSIDERATIONS

In this section, we describe some signal processing characteristics of the human which define the limits of his ability to acquire and to perfect motor skills. In the context of the engineering model, these are characteristics pertaining to pursuit and precognitive operation in limiting conditions. Because our point of view is both unifying and novel, the data we present are from diverse sources and are not complete.

LEARNING THEORIES.—Much of the traditional psychological literature on motor skills is either specific to a particular task or group of tasks or deals with observed quantities that are not particularly useful in a control engineering connection. If, however, we consider psychological learning theories more generally; i.e., as they were developed for more extended applications than to motor skills alone, we will note an emphasis on concepts that are highly relevant to a control engineering model. One can describe learning theories along a continuum anchored on one extreme in an emphasis on stimulus organization (the Gestalt theories) proceeding through a range of association and classical conditioning theories that emphasize stimulus-response time intervals to another anchor in Skinnerian (ref. 11) operant conditioning which emphasizes the organization of the responses.

The role of the stimulus-organization in learning has been emphasized by the Gestalt psychologists (e.g., Koffka, ref. 10) and expressed in terms of concepts such as closure, which approach the esthetic. Learning proceeds by insights attributable to a perceptual reorganization of the stimulus field which makes the problem's solution clear. In motor skills learning, we must define perception more broadly, so that in addition to conventional verbal responses, motor responses, (for example, manual control) can manifest or modify a perception or pattern in time or space. This emphasis on the structure of the input is shared by coaches and physical trainers. Trainers are interested in gross motor ability rather than in the fine muscular activity with which most human control behavior studies are concerned; however, the pragmatic attitude of the trainer forces on him insights that often elude others. For example, Harrison (ref. 12), in a detailed review of the neuromuscular bases for motor learning, comes to the conclusion that the prime emphasis in training should be put on organizing sensory inputs. This was expressed as follows: ". . . the role of the teacher is to give the chief sensory cue to the learner to use at the right time and let nature take its course . . ."

In terms of our model, the teacher serves as a device that first separates the input signal from input noise, and then emphasizes the predictability of the signal so that the trainee can select the proper output from his repertory of preprogramed responses.

To describe motor skills development, we must examine response as well as stimulus organization. Skinner, in his emphasis on emitted responses, has attacked this end of the problem. Skinner's emphasis on the response arises because, although one may not be able to isolate the specific stimulus that triggers a particular response, one can describe the regularities intrinsic in the patterns that the responses themselves define. It is as if we were describing the organism in terms of its ability to act as a free-running generator of responses, and only secondarily, if at all, addressing the phase synchronization of these responses with a stimulus or stimulus pattern. In the context of our model on figure 1, he has treated the rules that define how response patterns become incorporated into the pattern generator, and how they can be modified.

Insofar as motor skill is an example of the effective functioning of a control system, a synthesis of the foregoing polarized points of view is possible within a control engineering model.

RHYTHMIC TAPPING.—The data (refs. 13 to 16) which we examine will use highly organized inputs and responses (periodic functions in both cases) to manifest the limits of predictive human motor behavior.

Tapping in response to periodic inputs is a human output for which only the phase characteristic is definable. In this sense, it is a simpler task than conventional tracking problems. By examining the tapping literature, we can get information on two characteristics of human prediction: the extent to which prediction is, in fact, achieved; and the precision with which a periodic input is reproduced. The first is an equivalent of phase lag or advance. The second is a measure of the bandwidth of the output frequency generated in response to a single frequency input. The tapping equivalent of the effective and actual compensatory display is the conventional reaction time experiment in which a motivated subject attempts to minimize the delay between his response and the signal. A fully trained and altered subject produces a reaction time delay and associated variance which is a measure of neuromuscular limitations. For taps in response to a visual input, a 180 ms delay and a standard deviation of 15 to 20 ms are typical values. A subject tapping in an attempt to synchronize with a periodic signal represents an equivalent of a pursuit mode since the input rapidly becomes known to the subject. In general, synchrony is achieved within three or four periods. Characteristically, anticipation occurs as illustrated in figure 4.

At least as important a measurement, from the viewpoint of a subject approaching the precognitive mode of behavior, is the quality with which a periodic input is reproduced. The standard deviation σ of the stimulus-response interval for a periodic stimulus provides this measure. As shown on figure 5, the product of σ and input frequency $f=1/T$ is a constant of the order of 0.04 to 0.06 up to a minimum period T of 200 to 400 ms. At this point, frequency drifting begins and the product rapidly increases to a limiting value of $1/\sqrt{12}$. This limit represents a condition where the subject's response is selected from a rectangular distribution over the interval between stimuli T. The time interval 200 to 400 ms may represent a lower limit of a memory function that is able to maintain a constant σ/T up to this time interval.

PATTERN GENERATION.—Tracking data for square waves and sine waves are consistent with figure 5 (e.g., ref. 17). Complex combinations of sine waves have also been

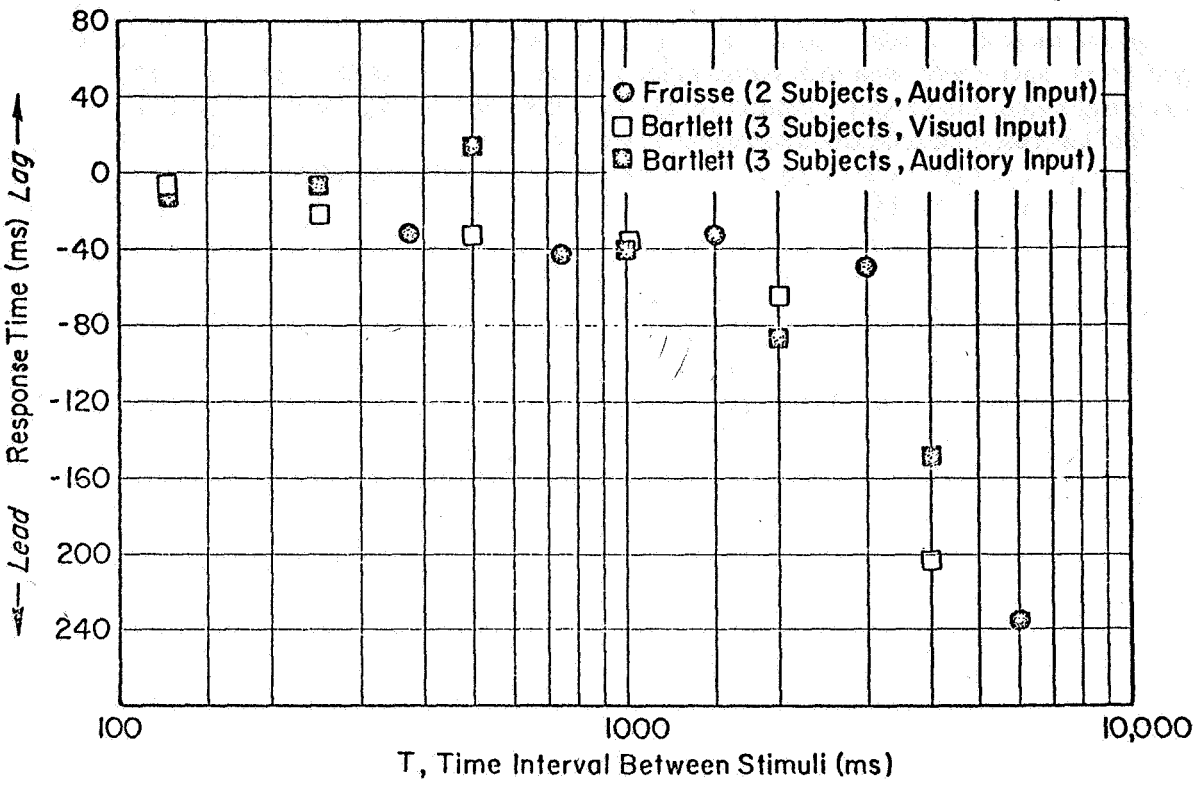

Figure 4.—Synchronization as affected by stimuli interval.

used to demonstrate the operator's ability to generate patterns and synchronize them. Vossius (ref. 9) created a periodic function of frequency 0.75 hertz, which consisted of a fundamental and its first two harmonics. This function was the input to a subject in an actual pursuit configuration. After a training experience of 20 to 30 periods, the input was removed during the course of pursuit tracking and the subject continued to recreate the input from memory. From figure 6, two points are clear: The open-loop generated pattern is not in phase with the input, and the open-loop pattern has a period that is about 10 percent longer than that of the closed-loop output.

Hess (ref. 18) demonstrated a similar finding in a study of human control of periodic, time-varying, plant dynamics. Using an actual compensatory display, a single frequency input of 1 rad/sec, and plant dynamics $Y_c(4)=9.66\ (1+0.5\cos 4t)$, he trained an operator for about 40 test runs and then blanked the error display for 8 to 9 seconds. Figure 7 indicates this blanking by double-headed, horizontal arrows. The stick movement is clearly unchanged in pattern, as in figure 6, but there appear to be phase and frequency changes. Clearly, the operator is not attending to the error in a closed-loop fashion. He is operating in a pattern generating or precognitive mode.

Pattern generation may not necessarily result in improved performance; however, if the major system consideration is that of stabilizing a divergent controlled element, the

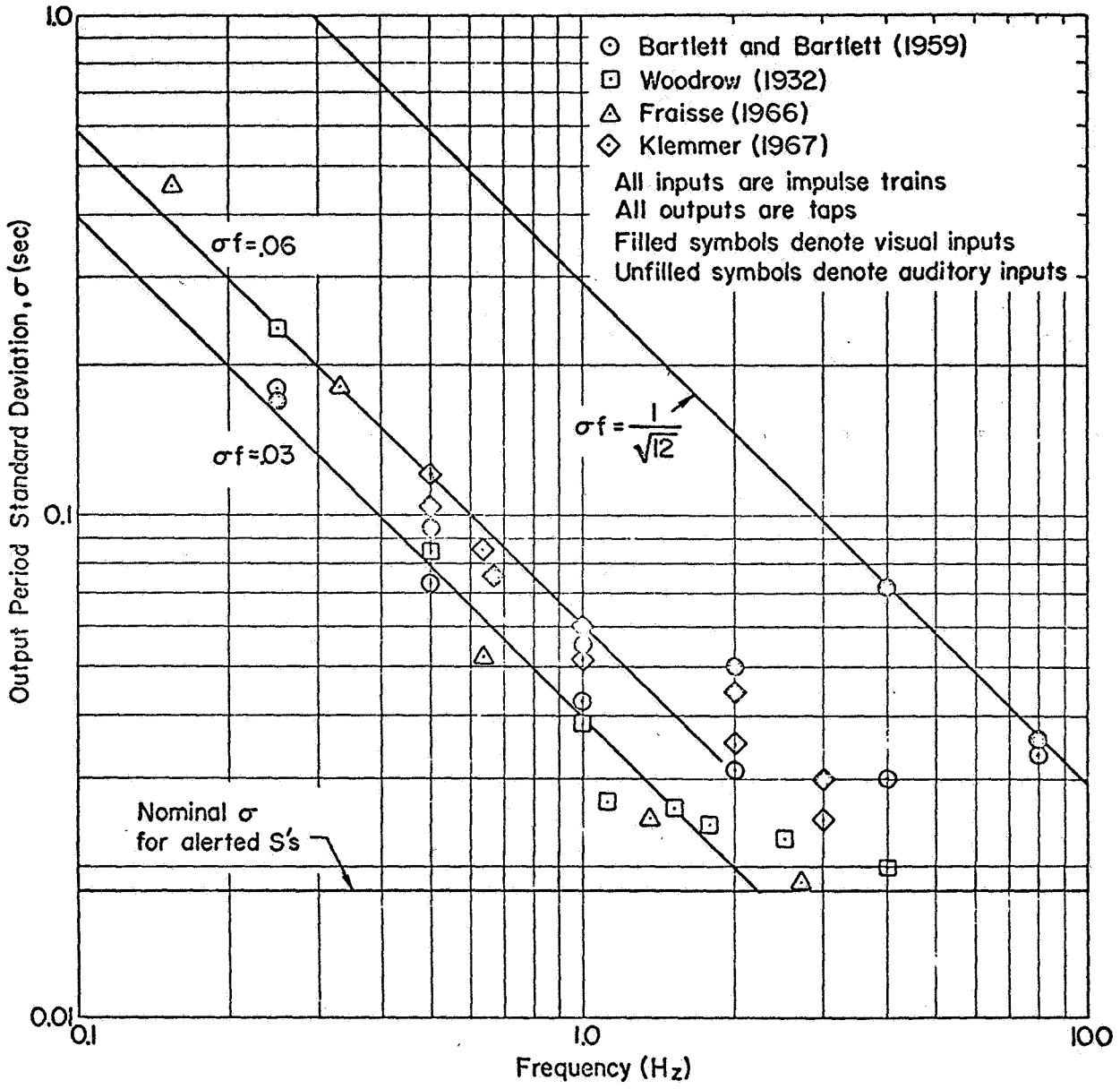

Figure 5.—Standard deviation of general period versus frequency of input function.

ability to predict may be critical. Smith (ref. 19) examined a human operator stabilizing a second order of oscillatory divergence. An actual compensatory configuration was used and the controlled element was:

$$Y_c(s) = \frac{K_c}{s^2 + 2\zeta_n \omega_n s + \omega_n^2}$$

where ζ_n is negative.

The experimental procedure consisted of presenting two subjects with an input consisting of four nonharmonic sine waves, 0.28, 0.74, 1.21, and 1.80 rad/sec, selecting a

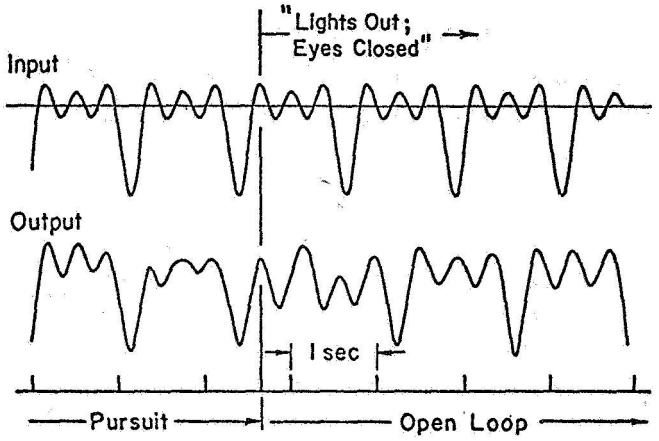

Figure 6.—Demonstration of synchronous pattern generation.

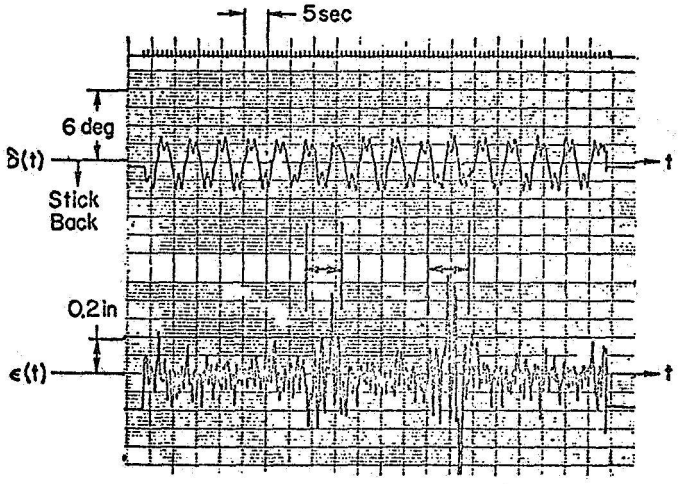

Figure 7.—Synchronous pattern generation stick output and error signal for oscilloscope blanking experiment.

value of ζ_n equal to -0.35 or -0.7 and increasing ω_n by discrete amounts on successive runs from 2.5 to 7.2 rad/sec until a maximum controllable value was achieved and maintained for a 2-minute run. It required 392 attempted runs of which 131 were successful, i.e., tracking was maintained for 2 minutes to establish controllability limits for ζ_n=-0.35 over the frequency range measured.

After this extensive training, Smith's subjects stabilized a divergent second-order plant, in an actual compensatory display, with a random appearing input where stability would not have been predicted from our knowledge of the possible characteristics of Y_{p_e} The effective delay time, T, for example, would have had to be of the order of the synaptic delays, or 20 ms. The trackers must have established a more effective control structure than the compensatory mode. Precognitive organization, by enabling the tracker to compensate for his inherent lags, made stable control realizable.

CONCLUSION

Starting with the most primitive configuration in which the human operator is a single input, single output element in single feedback control system, the familiar compensatory mode, a progression in system configurations explains how improvements in skill can arise in a servomechanism context. The pursuit mode, either by an actual physical configuration or as an effective reorganization as a result of learning, provides a mechanism whereby the feedforward necessary for compensating for the neuromuscular lags inherent in a human operator can arise. Ultimate skill arises when either actually or effectively the operator can predict his required control maneuvers and has the capability to execute them. The actual configuration can provide preview, but it is in modifying the effective configuration that the greatest challenge lies. In the effective precognitive mode, at a time determined by his prediction of the output signal's form, the operator releases a repertory of patterned responses that he has acquired by extensive experience and training.

When skill development is viewed in the foregoing context, a framework becomes available for including the psychological learning theories that emphasize the order and pattern of the input structure and insights, as well as the approach that emphasizes regularities in the output structure without attempting to isolate the input stimuli specifically. Furthermore, insights into the skill development process became possible which would not arise from more conventional psychological frameworks. For example, the possibility of measuring a short-term memory function for other than verbally mediated events is possible. Similarly, pattern recognition without verbal mediation becomes feasible. Lapses of skill may become understandable once the perceptual and training necessities for each level of skill are specified. Some accidents may be due not to shortcomings in motor control, but to a misapprehension on the subject's part of the control configuration in which he was operating. When we examine the precognitive mode, the evidence from such diverse sources as handwriting, tapping and tracking, and anecdotal studies of athletic skill improvement, all points in one direction. After familiarity with the plant dynamics has occurred and the operator has arrived at a beginning level of skill, further improvements occur as the operator can predict his required control responses. Characteristically, first a patterned output is emitted and then this output is properly phased with the appropriate stimuli.

We are beginning to be able to assign numbers to some of the quantities in this model for skill development. Thus, it appears from a consideration of much diverse data that the frequency spread of human generated single sine waves, as measured by σ of the drifting frequencies, is directly proportional to the interval between the periodic input signals up to a minimum interval T. Thus, $\sigma f = \sigma T = k$; where $k \simeq 0.04$ to 0.06 up to an interstimulus interval of 200 to 400 ms, at which point k increases to a limit of $\simeq 0.29$. From many sources, there is evidence that the synchronous manual generation of single sine waves can take place after only 3 or 4 input cycles. There is evidence that after hundreds of trial runs, an operator can exploit the regularities of the input and the controlled element to achieve an effective precognitive mode and stabilize systems under conditions previously thought to be impossible.

Much more quantitative data is needed to extend the usefulness of the SOP theory of skill development. With more data we will become able to design for ultimate skill. We will also attain valuable new insights into human information processing behavior.

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